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The Value of Rain: Benefit-Cost Analysis of Rainwater Harvesting Systems

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Abstract Rainwater harvesting is increasingly viewed as a practical means of reducing stormwater runoff and supplementing water supply in water-scarce regions, although its widespread adoption has been limited in urban areas. While a number of studies have examined the potential of rainwater harvesting to reduce potable water use, stormwater runoff, energy associated with delivering potable water supplies, or the associated costs, none have assessed these costs and benefits collectively. Using a densely urbanized watershed in southern California as a test case, this study quantifies the economic benefits and costs of rainwater harvesting to investigate whether capturing and using rainwater can be an efficient regional policy. Given the watershed's land use, topography, and rainfall variability, a range of cistern sizes is evaluated to estimate the magnitude of water, energy and carbon savings for two rainwater use scenarios: outdoor use only and outdoor plus non-potable indoor use. With water prices held constant, only the smallest cistern (208 l) used for outdoor irrigation is efficient from an economic standpoint. In contrast, with a modest annual increase in water rates over the life of the project, the study shows that rainwater capture for outdoor use is an efficient policy for any cistern size. Finally, due to the higher installation and maintenance costs required to pipe the water indoors, outdoor/indoor uses show only modest economic benefits. The potential volume of water captured annually is significant, depending on the cistern size, equivalent to the total water needs of 13,345 to 31,138 single-family residences.

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1 Introduction

Growth of urban communities has created significant challenges for water management. In southern California, for example, most cities rely on water transported hundreds of miles to insure adequate local supplies. Paved and impervious surfaces in urban areas disrupt the natural processes of filtration and infiltration of rainwater, consequently increasing runoff volume and impairing water quality in local waterways. This compromises public safety through increased flooding, and adversely impacts the ecology, geomorphology, and socioeconomic benefits of the receiving waters (NRC 2008; Dallman and Piechota 2010).

Public attention is turning increasingly towards the potential value of rain. Capturing and reusing rainwater is regarded by some sectors of the public and policy-making community as a potentially viable strategy both for supplementing local water supply and for reducing pollution from stormwater runoff (Walsh et al. 2014). By using captured rainwater urban residents can avoid unnecessary use of potable water for non-potable uses, such as landscape irrigation, while also reducing the volume of stormwater runoff carrying pollution to rivers, lakes, and beaches. Potential potable water savings resulting from rainwater capture may be significant in urban areas, especially in semi-arid regions like southern California where landscape irrigation accounts for at least half of all urban potable water use (Hanak and Davis 2006). Reduced demand for potable water also translates to energy savings and associated carbon emission reductions. These two resources are closely linked, as water is required to produce energy and energy is required to transport, treat and distribute water (Ruberto et al. 2013).

A number of studies have examined the feasibility, cost and performance of rainwater harvesting systems (RWHS) both to augment water supply and as a stormwater management solution. Gilroy and McCuen (2009) modeled the effect of installing a cistern at single-family residential buildings, and predicted substantial reductions in runoff volume and peak for one- and two-year design storms. At a neighborhood scale, Steffen et al. (2013) observed that installing a 190 l cistern at residential buildings would produce up to 50 % water saving efficiency for non-potable indoor use in humid regions of the U.S. (Midwest and East Coast) and reduce runoff volume by up to 20 % in semiarid regions such as the Southwest. Runoff volume reductions of up to 12.5 % were projected for a watershed in San Diego, California if 7571 l cisterns were installed at all residential buildings in the watershed (Walsh et al. 2014). Debusk et al. (2013) examined the performance and economic benefits of several large-scale RWHS installations in southeastern U.S. They found that costs and effort required to implement RWHS outweighed the benefits of water savings in some cases, and recommended that additional benefits, such as stormwater reductions, be considered in evaluating economic efficiency. From the supply side, several studies have sought to determine the optimal size cistern to ensure a continuous supply of harvested rainwater given seasonal variability of precipitation and water use (Wang and Blackmore 2012; Arora et al. 2013; Jung et al. 2015). Relying solely on rainwater to meet non-potable needs was found not to be economically feasible in areas with high climate variability, but it can still provide for a significant portion of demand.

The potential energy savings of RWHS have also been investigated in several studies. Malinowski et al. (2015) estimated that in the U.S. up to 3.8 billion kWh of energy, valued at US$270 million, could be saved annually by replacing potable water used for landscape irrigation and other outdoor water uses with rainwater. They found, however, that energy and associated cost savings per household are low, up to 120 kWh with savings of less than US$10 per year. Vieira et al. (2014) and Wang and Zimmerman (2015) note that the performance of RWHS varies based on local characteristics such as water demand, system design, water-energy intensity and building type. In addition, Elkind (2011) noted that greenhouse gas emissions associated with water-related energy consumption total more than 100 million metric tons of carbon dioxide-equivalent gases, while the burning of carbon-based fuels to power California's water infrastructure releases particulate matter that can cause asthma and other health effects. Thus conserving water also means conserving energy and reducing pollution.

While previous research has examined the energy savings or the potential reductions of potable water use and stormwater runoff from RWHS, few studies have comprehensively assessed these costs and benefits on a regional scale. This paper breaks new ground in predicting a range of lifecycle costs and benefits from implementing RWHS at both residential and commercial buildings. The benefits considered include reduction in runoff volume and peak runoff, savings in potable water and energy, and reduction in carbon emissions. Costs considered are those incurred by the building owner to purchase, install, operate, and maintain the infrastructure needed for RWHS (cistern, pump, pipes). A benefit-cost analysis is conducted to predict the net benefits of implementing RWHS, using a densely urbanized watershed in southern California as a test case (Fig. 1).

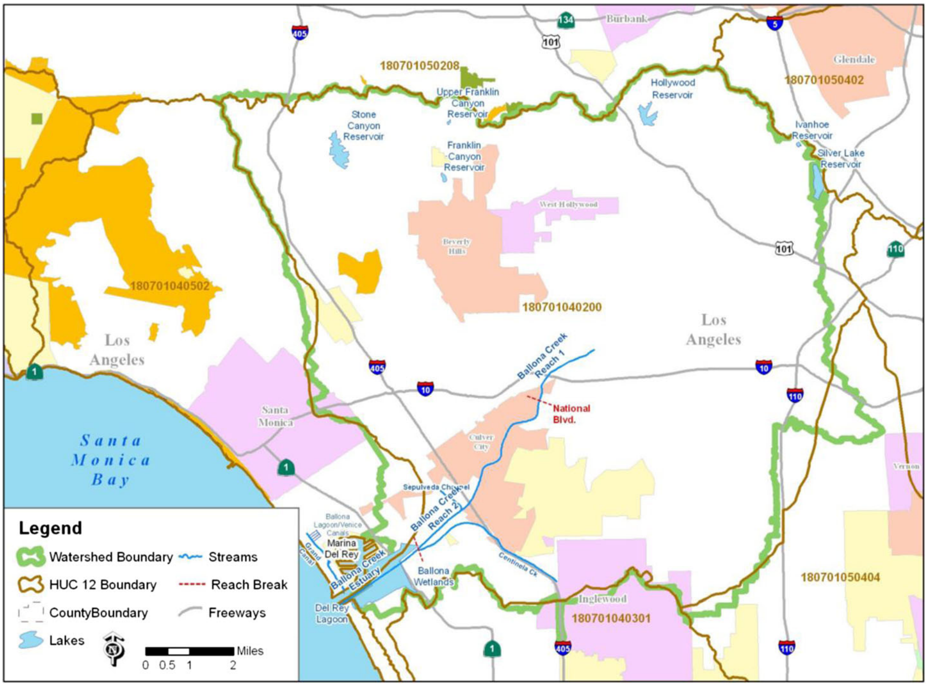

Fig. 1 Ballona Creek Watershed (Source: Los Angeles Regional Water Quality Control Board (2012))

2 Methodology

In order to assess total economic value of RWHS, this project relied on established engineering frameworks to estimate stormwater reductions and water and energy savings. The U.S. Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) (Rossman 2010) was used to generate estimates of reductions in stormwater quantity and potable water savings, based on type of use (outdoor only or indoor and outdoor) and size of cistern installed. In parallel, energy savings and associated carbon footprint reduction were quantified for the same set of implementation scenarios.

Estimates of water and energy savings were then converted into dollar figures based on cost data from the literature. These monetary values were integrated into a benefit-cost framework to assess the economic efficiency of adopting rainwater capture for various scenarios in the Ballona Creek watershed.

2.1 Quantifying Stormwater Reduction and Potable Water Savings

The quantity of water that can be collected by a cistern depends on numerous local variables including rainfall pattern, land use distribution, roof sizes, cistern size, extent of participation, use of harvested rainwater, and usage rate of collected water (Vieira et al. 2014) which in turn depends on factors such as evapotranspiration (ET) and indoor use demands. The following assumptions were made to estimate potable water savings and stormwater quantity reductions of RWHS in the Ballona Creek watershed:

1. Cisterns are installed at residential and commercial properties, which comprise approximately 75 % of total land use.
2. 50 % of residential and commercial buildings adopt RWHS, with each participating building installing one cistern.
3. Rooftops in residential or commercial neighborhoods account for 70 % or 60 % of the imperviousness in their respective areas, with the remainder composed of streets, parking lots, walkways and driveways.
4. Average lawn size is 93 m^2 per building with warm-season turfgrass the typical landscape, irrigated every 48 h.

The following water balance equation quantifies the volume of rainwater that can be captured considering the assumptions stated above:

$$\frac{\partial v}{\partial t} = q_0 - q_1 - q_2 \tag{1}$$

where V is the volume of water stored; q_0 is roof runoff that enters the cistern depending on the duration and rate of rainfall and the roof size; q_1 is rainwater that is discharged from the cistern to meet demands such as lawn irrigation and/or indoor uses; q_2 is overflow from the cistern when capacity of the cistern is exceeded; t is simulation time interval. Units for $q_{0,}$ q_1 , and q_2 are $[L]^3/[T]$, and V is in $[L]^3$.

Rainwater that leaves the cistern as q_1 represents both the volume of potable water saved and volume of runoff reduced by the RWHS; these depend on type of water use, ET, lawn size, and water use rate. To quantify runoff volume and peak runoff reduction and potable water savings over a long-term period, Eq. 1 must be solved considering all participating buildings in the watershed, spatiotemporal variability in climate, basin characteristics such as land use and topography, and existing stormwater drainage infrastructure. To better capture heterogeneity in climate and basin characteristics, the 337 km^2 watershed was divided into 1414 subwatersheds based on topography and existing stormwater collection networks. Average size of the subwatersheds is 0.163 km^2.

Land use data for the watershed was obtained from Los Angeles County Department of Public Works (LACDPW 2005) and was used to estimate the percentage of residential and commercial land uses in each subwatershed. Percent imperviousness was inferred from an imperviousness map of the watershed obtained from the U.S. Geological Survey (USGS 2014). Average roof size of 148.65 m^2 was used for buildings based on the study by Fried et al. (2014). With these data and assumptions, the number of residential and commercial buildings was estimated in each of the subwatersheds. The aggregate number of commercial and residential buildings was estimated as 449,752. This estimate was within 2.8 % of the number of dwelling units calculated for the watershed using the methodology proposed for cities in California by Washburn et al. (2010). Based on the assumed 50 % participation rate, a total of 224,876 residential and commercial buildings in the entire watershed would implement RWHS.

Two rainwater use scenarios were considered for the analysis, each modeling different sizes of cisterns to determine the economic efficiency of various scales. In the first scenario, the harvested water was assumed to be used for lawn irrigation only; the second scenario considered both lawn irrigation and non-potable indoor uses. Indoor use was limited to toilet flushing and laundry. Water demand for lawn irrigation was estimated from daily ET data obtained from the California Irrigation Management Information System station in Santa Monica, California which is near the case study watershed. Irrigation demand was determined as the difference between total ET and total rainfall since the last irrigation. Rainfall data at three gauges in the watershed was obtained from LACDPW for 15 mins intervals. Proximity and altitude criteria were used to define the rain gauge that represents each subwatershed.

Non-potable indoor use rate was estimated based on daily sewage flow estimates of 378 l/person/day for residential and commercial areas in Los Angeles (City of Los Angeles 2005). Toilet flushing and laundry were assumed to account for 50 % of the daily per capita sewage flow (Mayer and DeOreo 1999). U.S. Census data for the city of Los Angeles estimates average household size and average number of employees for commercial buildings as 3 and 3.5, respectively (U.S. Census Bureau 2015). Consequently, non-potable indoor water use rate of 25.6 l/h per participating building was used for the analysis. Hourly variability in indoor use rate was modeled using an hourly demand pattern guided by Butler (1993).

Six different cistern sizes, ranging from 208 l to 7571 l were analyzed to examine sensitivity of benefits and costs to cistern size. SWMM was used to solve Eq. 1 for each cistern size and water use scenario combination to predict water savings and reductions in stormwater quantity at the watershed scale and for each one of the 1414 subwatersheds. SWMM was calibrated for the watershed by a previous study (Muleta et al. 2013).

2.2 Calculating Energy Savings

Southern California's water systems are uniquely energy-intensive due to the pumping requirements of major inter-basin conveyance systems which move large volumes of water long distances (Wilkinson et al. 2006). Pump stations also use significant portions of energy, up to 90 % of the energy expended in water supply and treatment systems, to provide appropriate pressure for transporting and delivering treated drinking water through pipe networks.

The regional water wholesaler, Metropolitan Water District of Southern California (MWD), obtains water from two main sources: the State Water Project (SWP), originating in northern California, and the Colorado River. In Ballona Creek watershed, most of the municipal supply is purchased from MWD by local water agencies, primarily the Los Angeles Department of Water and Power (LADWP), with a small portion coming from locally produced groundwater or reclaimed wastewater (LADWP 2014). Approximately 2638 kWh are required to pump one megaliter (ML) of SWP water from northern California to the MWD service area (DWR 2015). This untreated water is delivered to treatment and distribution systems within southern California. MWD (2016) estimates approximately 1621.4 kWh/ML are required to pump Colorado River water to southern California.

In this analysis, MWD's Colorado River energy intensity factor of 1621.4 kWh/ML is used to calculate energy savings of RWHS. This figure is chosen as a very conservative estimate without including energy use for treatment and water distribution system-level pumping. Carbon footprint reductions are calculated using EPA's equivalence factor of 6.89551×10^{-4} metric tons CO_2 / kWh (EPA 2014).

2.3 Benefit-Cost Model

The benefit-cost analysis (BCA) compares the benefits of reduced potable water use with costs of implementing and maintaining RWHS. Assumptions in the BCA are as follows:

1. Water captured by rainwater harvesting does not increase property owners' overall water use but results in a permanent reduction in water purchased by the water utility. There is no "rebound effect" assumed. Rebound effect occurs when an improvement in technology does not result in net savings but instead users increase their water use (Berbel et al. 2015).
2. Stormwater benefits of RWHS such as water quality improvements or reduction in flood risk and damage due to reduced runoff peak and volume are not included in this BCA. While analyzing water quality benefits of RWHS is beyond the scope of this study, flooding benefits were excluded as no substantial flood damage reduction is expected for the watershed, based on the results of the SWMM modeling (see Section 3.1).
3. The benefits of rainwater capture included are those from the economic value of water, energy and carbon emissions saved. Rainwater capture can also be a source of intrinsic satisfaction or personal pride for the property owner, because they believe in the importance of saving water even when the costs exceed the monetary benefits. This BCA excludes such intangible benefits.
4. Cost per cistern remains constant regardless of the number of cisterns purchased. It is likely that if the city buys a large quantity of cisterns, a lower unit cost could be negotiated, however no bulk purchase discount is assumed here.
5. With a fixed 50 % participation rate, benefits per cistern remain constant. Testing the sensitivity of participation rates to determine if there is an upper or lower threshold at which the magnitude of additional benefits changes was not included in this study.
6. Costs of purchasing and installing RWHS are paid in full upon implementation, but benefits from water, energy and carbon savings accrue every year until the end of the project's service life, assumed as 30 years in this study.

Assumptions (2) and (3) could underestimate the true benefits of RWHS, and assumptions (4) and (5) could overestimate the true costs. In this vein, the BCA takes a very conservative approach and true net benefits are likely to be higher than these estimates. The present value of net benefits from each specification of the RWHS is calculated as follows:

$$Discounted\,Net\,Benefits = \sum\nolimits_{t=0}^{t=29} \frac{B_t - C_t}{(1+r)^t} \tag{2}$$

where B_t denotes total benefits in year t and C_t denotes total costs in year t. Benefits include monetary value of saved water, carbon emissions, and energy (regional benefits). Costs include fixed costs of purchasing and installing the RWHS, and associated operating and maintenance costs. Discounted net benefits of the RWHS are calculated for each scale (cistern size) and for the two scenarios: outdoor use only, and outdoor and indoor uses. The scale and scenario with the highest discounted net benefit is the most efficient RWHS for Ballona Creek watershed.

2.4 Baseline Parameters

2.4.1 Economic Value of Saved Water

There are a number of ways to determine the value of potable water saved by implementing RWHS, such as direct market valuation or replacement cost (Vivas and Maia 2013; Matos et al. 2015). The economic value could be measured based on the value of this water for the next best use. For example, the saved rainwater could be valued as water not imported, remaining in its source area to improve environmental conditions. The value could also be measured by the price paid by MWD for additional water needed to meet future urban needs, for example purchasing water from farmers in the Central Valley. Another measure of value could be the money saved by consumers for reduced use of munucipal water, based on rates charged by various water agencies.

Given that most of the water supply in Ballona Creek is purchased from MWD, their wholesale price to water agencies seemed most appropriate for this study. The Tier II Full Service Treated Volumetric Cost charged by MWD is used as the value of saved water. In 2015, this price was US\$1055 per acre-foot (US\$0.86/m^3) (MWD 2016). The BCA considers the case of a fixed cost of water for the project duration, and the more realistic scenario of an annual water rate increase of 5 % to reflect increased overhead costs. This value is consistent with MWD's average rate increases since 2005 (MWD 2016).

2.4.2 Social Cost of Carbon

The dollar valuation of carbon emissions saved is based on the federal Executive Order 12,866 Interagency Working Group's 2013 estimate of the Social Cost of Carbon (SCC), which is US\$40.45 per metric ton of carbon (IWG 2013). From a global perspective, this U.S. estimate for the social cost of carbon is lower than other national estimates. For example, the mean price from a review of peer-reviewed literature is US\$43 per metric ton of carbon (Banasiak et al. 2015). A review of SCC prices by Tol (2005) ranges from US\$14 to \$165, with a mean estimate of US\$93 per metric ton. Our study uses the IWG's value because federal government estimates are more likely to be used in benefit-cost analyses of public policies.

2.4.3 Energy Costs

Energy savings are valued at US\$0.21/kWh, based on the average energy price for Los Angeles County (Bureau of Labor Statistics 2016).

2.4.4 Cost of Cisterns

To estimate RWHS equipment and installation costs, price data was collected from popular vendors of rainwater cisterns and associated equipment, such as home improvement stores and online specialty vendors. Average market prices in southern California were used in the model. For outdoor only use gravity flow is assumed, thus there are no energy or pump replacement costs (Table 1). When rainwater is used for outdoor and indoor uses, the cost of the cistern is the same, but costs for labor and materials are much higher. Materials include pipes and pumps to deliver the water indoors for non-potable uses. For indoor water use cisterns are equiped with a one horsepower pump operating at 60 % pump efficiency, replaced twice during the project lifetime. Costs for potential subterranean installation are not considered.

2.4.5 Discount Rate

There is wide disagreement on the proper discount rate for long run projects, in part because of the long time horizons involved and because of intergenerational equity concerns. Sunstein and Weisbach (2009) provide a comprehensive summary of the thinking behind various approaches to discount rates, which found that assumptions for the most appropriate discount rate range widely. For example, Stern (2006) used 1.4 % discount rate in his landmark study of climate change, while Nordhaus (2007) used an estimate of 4.3 %. This study uses a 3 % discount rate, which aligns with the recent Regulatory Impact Analysis for EPA's Clean Power Plan, a significant greenhouse gas regulation that also uses a 3 % discount rate (EPA 2014).

3 Modeling Results

3.1 Stormwater Reduction and Potable Water Savings

Long-term SWMM simulation was conducted using rainfall and ET data from 2000 to 2010, which includes both wet and dry years. Figure 2 shows annual average volume of potable water

Table 1 Fixed and O&M costs of cistern installation (USD)

	Cistern capacity (liters)					
Outdoor use only	208	379	946	1893	3785	7571
Cost of the cistern	$150	$350	$450	$500	$650	$800
Installation cost (labor)	50	200	200	200	200	200
Installation cost (materials)	50	150	200	250	300	350
Total fixed cost, outdoor	$200	$700	$850	$950	$1150	$1350
Outdoor and indoor non-potable use	208	379	946	1893	3785	7571
Cost of the cistern	$150	$350	$450	$500	$650	$800
Installation cost (labor)	500	500	500	500	500	500
Installation cost (materials)	300	350	400	450	500	550
Total fixed cost, outdoor & indoor	$950	$1200	$1350	$1450	$1650	$1850
Energy cost (per year)	$27	$27	$27	$27	$27	$27
Pump replacement (per 10 years)	$200	$200	$200	$200	$200	$200

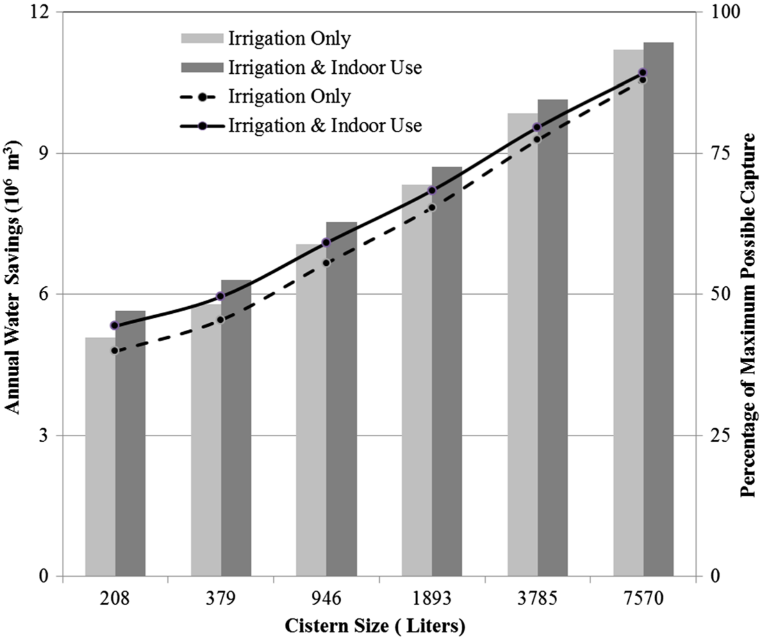

Fig. 2 Average annual water savings (*bar graph*) and percentage of maximum capture obtained (*line graph*) for various cistern sizes and water use scenarios at the watershed scale

that could be saved if cisterns of various sizes are installed at 50 % of residential and commercial buildings in each Ballona Creek subwatershed. The result clearly demonstrates sensitivity of projected water savings to cistern size and, to a lesser degree, to water use scenario. To further elucidate these sensitivities, maximum possible annual water saving of 12.74 million m^3 was calculated for the watershed as the product of the number of buildings that participated in the program, average roof area of the buildings and average annual rainfall in the watershed during the simulation period (381 mm). Percentage of the maximum possible water savings captured using cisterns of various sizes is also shown in Fig. 2. The smallest cistern size considered saves less than half of the possible annual capture whereas the largest cistern would capture close to 90 % of the maximum rainfall volume. To put these figures in perspective, assuming water consumption for a single family residence averages 360,617 l per year (based on LADWP's's (2015) estimate of 261 gal/day/household), this analysis shows that capturing and reusing rainwater can save enough potable water to provide for 13,345 to 31,138 single family residences each year, depending on the cistern size.

Reduction in the average annual volume and peak flow of stormwater generated in the watershed ranges from 11 % and zero, respectively, for the smallest cistern for outside use only to 24 % and 14 % respectively for the largest cistern considering both irrigation and indoor uses. Projected peak flow reductions are not substantial, as peak flows are the result of high intensity and long duration rains that would quickly fill the cisterns, thus compromising their peak flow reduction effectiveness. As stated earlier, the stormwater quantity benefits projected here were not translated into monetary benefits as Ballona Creek is designed to accommodate runoff from a 50-year frequency storm event (LACDPW 2004). As such, flood damage reduction benefits of RWHS were considered minimal for the case study watershed. This would not necessarily be the case for other watersheds.

3.2 Energy Savings

Annual energy savings are plotted for irrigation only versus irrigation and indoor use as a function of different cistern sizes (Fig. 3). As cistern size becomes larger, the annual energy savings increases. Both water use scenarios show similar levels of energy savings. Annual reductions in carbon equivalence show a similar pattern to energy savings, with increasing trends for larger cistern sizes. Likewise, the two water use cases provide fairly similar reductions in carbon equivalence.

3.3 Results of BCA

The results of the BCA reveal how the costs of installing RWHS compare with the benefits of capturing and reusing rainwater. Results are summarized in Fig. 4, showing results for constant water price and with increasing water price at 5 % per year.

When water price is constant during the project horizon, discounted net benefits of indoor water use are negative for all scales of RWHS. Costs of purchasing, installing and maintaining the equipment far exceed the benefits of water, energy and carbon saved. Larger cisterns have lower discounted net benefits than smaller cisterns, indicating increasing volume of water captured will not change the result. The only scale and scenario that has positive net benefits is the smallest cistern for outdoor use only. In this case, benefits outweigh the costs by about US$64.8 million (M). Discounted net benefits are negative for other cistern sizes for outdoor use only.

If water prices increase annually, the results change dramatically. Outdoor use has positive discounted net benefits for all cistern sizes, although the smallest cistern still has the highest discounted net benefits (US$151.8 M). The stark difference in results is for the outdoor and indoor use scenario when price of water increases. After an initial drop from 208 to 379 l, larger cisterns have increasingly higher discounted net benefits. The largest cistern has discounted net benefits of US$49 M. Increasing water prices makes indoor water use, and installing larger cisterns, economically viable over the long term.

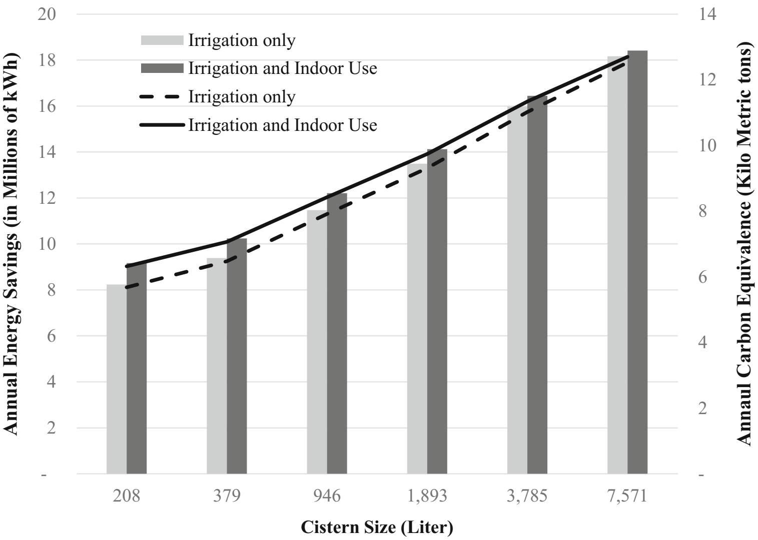

Fig. 3 Average annual energy *(bar graph)* and carbon savings *(line graph)* for various cistern sizes

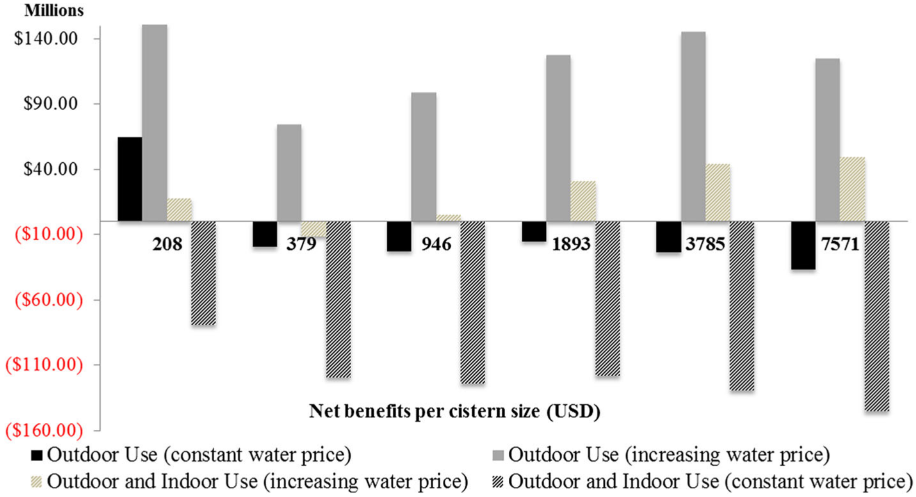

Fig. 4 Discounted net benefits of RWHS in Ballona Creek watershed

Overall, the highest discounted net benefits are for the smallest cistern. If water prices are constant for the project horizon, net benefits of RWHS for indoor and outdoor use is never positive. Therefore, the model suggests that RWHS should not be adopted for indoor use if water prices stay constant at current rates. If water prices are expected to increase, at least at 5 % per year, larger cisterns can also be considered. Although the most efficient scale is still 208 l, the practicality of indoor use for such a small capture volume must be considered.

The spatial distribution of discounted net benefits in the watershed varies based on geographic characteristics (Fig. 5). Subwatersheds with higher population density and impervious surfaces have higher discounted net benefits. Although not visible in the map, geospatial analysis reveals distinct spatial correlation between the projected water savings, land use and imperviousness distributions, and discounted net benefits in the watershed.

4 Discussion

The results of the BCA model suggest that the most economically efficient specification for a rainwater capture program in Ballona Creek watershed will be 208 l cisterns. This cistern size is the most efficient regardless of whether water prices increase. In the latter scenario of increasing water prices, discounted net benefits are three times higher than the scenario of constant water prices. Cost of cisterns are low and thus benefits are substantial.

Overall, the BCA shows that the largest share of benefits is from water savings (potable water purchases replaced by captured rainwater). For example, for 208 l cisterns installed for outdoor use only, annual water savings comprise 70 % of total benefits (US$4.3 million), while energy and carbon savings comprise 27 (US$1.7 million) and 3 % (US$230, 000) respectively. This implies that the price of water is a critical component in determining the most efficient policy. If water prices are going to stay at the same rate for the project lifetime it is not worthwhile to capture rainwater for indoor use, regardless of the cistern size, although outdoor water use is still cost efficient. If the price of water is to increase at a modest rate of 5 % per

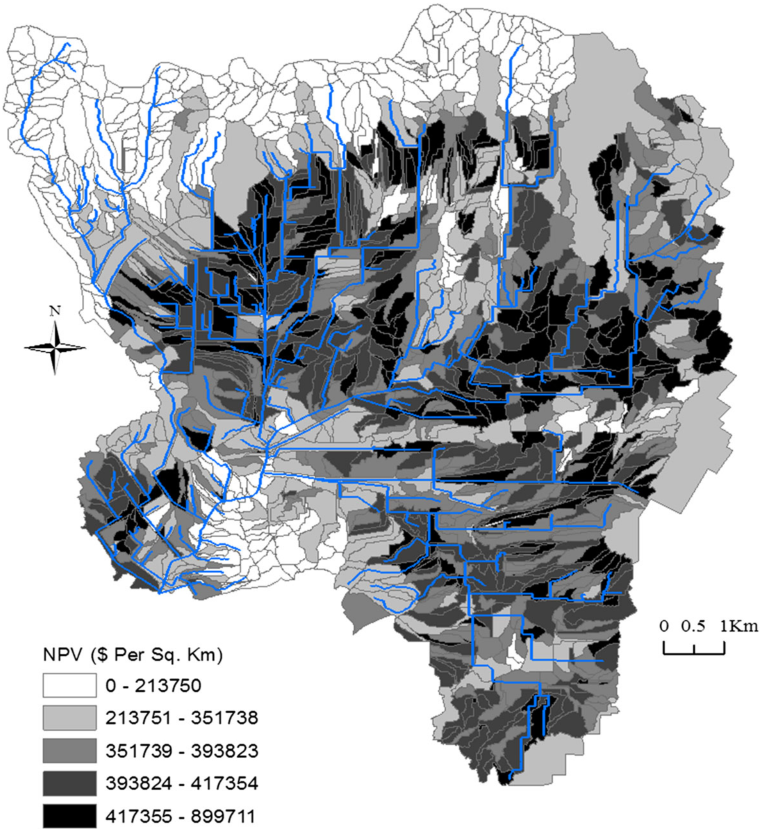

Fig. 5 Spatial distribution of net present value in U.S. dollars per km^2 per subwatershed, for the 208 l cistern and outdoor irrigation use

year, net benefits of RWHS are positive, regardless of cistern size. As an example, in the outdoor use only scenario for 208 l cistern, discounted net benefits amount to US$64.8 million, but when water price increases, discounted net benefits for the same scenario increases to US$151.8 million. The price of water supplied to the watershed is the most significant parameter that determines the stream of benefits from capturing and reusing rainwater.

The BCA estimates should be viewed as conservative. As noted earlier the BCA does not include benefits for water quality, flood reduction, or non-market values derived from personal satisfaction. The analysis used very conservative values for energy savings and the price of carbon. Therefore, the benefits of RWHS are likely to be higher than what is estimated here. Also, if cost of cisterns can be lowered through bulk discounts or if the payment for the cisterns can be spread over many years rather than a single payment in the first year, it can potentially make indoor use more efficient as well.

5 Conclusions

This paper presented a methodology for conducting a BCA of RWHS at residential and commercial buildings to substitute portions of potable water from the water utility in an urban area. The main finding is that benefits of rainwater harvesting in Ballona Creek watershed for most cistern sizes far exceed the costs of implementation and operation. Even holding water price constant, it is economically efficient to pursue a wider adoption of RWHS for the smallest cisterns that capture water only for outdoor uses. Costs of larger cisterns that allow for indoor use are not justified when water prices are constant, but when price of water increases annually, benefits exceed the cost. Price of water is therefore a critical factor in determining whether adoption of RWHS is a rational policy, and its optimal implementation scale.

This research can inform public policy on a potentially cost effective way to supplement water supplies, enhance water conservation and reduce resource use without increasing investment in piped water infrastructure, costs typically borne by ratepayers. This is valuable information for policy makers and water managers for deciding whether and in which locations to incentivize the adoption of RWHS. The rigorous analysis conducted for this study found significant spatial correlation between the projected water savings, land use and imperviousness distributions, and discounted net benefits within the watershed. This could enable city engineers and water managers to identify areas where RWHS may be prioritized based solely on readily available watershed land cover data.

Further analysis could test the sensitivity of different water rate increases and increasing energy costs, or of varying participation rates and seasonality to determine if there is a minimum or maximum volume of cisterns at which the magnitude of additional benefits changes. While beyond the scope of this study, expanding the BCA to include water quality and flood reduction benefits from reduced stormwater volume would provide a more comprehensive accounting and further increase the net benefits of RWHS.

Compliance with Ethical Standards The authors have no potential conflicts of interest related to this research. No outside funding sources were utilized to support this study. Human subjects were not involved in this research.

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